Looking to the Future: Non-contact Methods for Measuring Streamflow

by

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Abstract

We have conducted a series of proof-of-concept experiments to demonstrate whether it is possible to make completely non-contact open-channel discharge measurements. After an extensive evaluation of potential technologies, we concluded a combination of high-frequency (microwave) radar (for measuring surface velocity) and low-frequency radar (ground-penetrating radar) for measuring channel cross-section, had the best chance for success. The first experiment in 1999 on the Skagit River, Washington, using non-contact methods, produced a discharge value nearly exactly the same as from an ADCP and current meter. Surface-velocity data were converted to mean velocity based on measurements of the velocity profile (multiplied by 0.85), and radar signal speed in impure fresh water was measured to be 0.11-0.12 ft/ns. The weak link was thought to be the requirement to suspend the GPR antenna over the water, which required a bridge or cableway. Two contractors, expert with radar, were unsuccessful in field experiments to measure channel cross-section from the riverbank. Another series of experiments were designed to demonstrate whether both radar systems could be mounted on a helicopter, flown back and forth across a river, and provide data to compute flow. In Sept. 2000 and May 2001, a series of helicopter flights with mounted radar systems successfully measured surface velocity and channel cross-section of the Cowlitz River, Washington.

Introduction

The basic method by which flow in open channel is measured at streamgaging station has not changed for over 100 years. A current meter with a rotating propeller or cups, stabilized by a heavy lead weight, is lowered into the river. The velocity of flow at a point is proportional to the rate of rotation of the rotor during a measured period of time (Rantz, 1982). Multiple depth and velocity measurements are taken across the channel, and calculations of discharge over these sub-areas summed to give the total stream discharge. These discharge values are used to define a relation between the stage (depth) and rate of flow (discharge), referred to as a stage-discharge rating curve. During floods, direct measurement of flow with a current meter or any other instrument that must be placed in the water could introduce high measurement errors, and pose safety hazards to personnel. At times, conditions can be sufficiently hazardous so that no current-meter measurement can be made. When discharge measurements are not available, the stage-discharge relation is defined by indirect methods, which are less accurate than direct measurements. Lower-quality high-flow data mean less accurate estimates of flood-frequency and delineation of flood-inundation areas.

Primarily for reasons of safety, but also with expectations of faster and lest costly data collection, the USGS initiated a research project to leap-frog the technology of streamgaging by a decade. After much thought and discussion, it was decided to explore the possibility of direct measurement of streamflow without having to place any instruments in contact with the water.

A variety of technologies were examined to determine the most likely methods to measure key surface-water characteristics needed to dompute flow. Results are shown in Table 1. Note that no method offers the chance to measure mean velocity by non-contact methods, but high frequency (microwave) radar could measure surface velocity, and low frequency radar has the possibility of measuring water depth and cross-section.

Table 1. Evaluation of New Technologies for Discharge Measurement in Natural Rivers (Instrument Sensor not contacting the water)
1 = Field tested; 2 = Possible but not field tested; 3 = Not possible

Technology	Stage	Water Depth	Surface Velocity	Mean Velocity
Acoustics	1	3	2	2
Laser	2	1*	2	2
Image Method	2	3	2	3
Low Frequency Radar	2	1	2	3
High Frequency (Microwave) Radar	1	3	1	3

Radar Capabilities

Low-frequency radar technology has been widely used in geophysical applications, including hydrology. The USGS has used ground penetrating radar (GPR) on water bodies in hydrologic (Beres and Haeni, 1991) and bridge scour studies for many years. These studies used GPR systems with 80- to 300-megahertz (MHz) antennas. Penetration of the water column and subsurface was dependent on the depth and electrical conductivity of the water, the conductivity of the sediments, and the frequency and power of the radar antennas. The antennas were either floated directly on the water or were placed in the bottom of a rubber raft so that they were essentially in contact with the water. A GPR radar antenna (100MHz center frequency) was suspended from a cableway and successfully measured the channel cross-section in four unstable stream channels draining Mount St. Helens, Washington with suspended sediment concentrations as high as 10,000 mg/l (Spicer and others, 1997).

Velocity of radar waves in impure freshwater is partly controlled by water conductivity and temperature (Fig. 1). Conductivity of about 1,000 microSiemens/cm or greater can completely absorb radar energy, and values of 300-400 microSiemens/cm in the San Joaquin River, California, greatly limited penetration depth and signal resolution. High conductivity water would preclude the use of GPR in estuaries and some rivers.

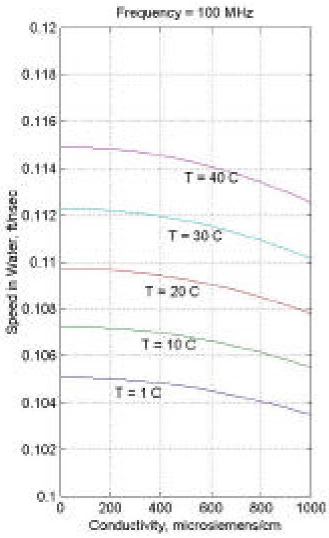

Fig. 1. Effect of conductivity and temperature on speed of radar wave in impure fresh water.

High-frequency Doppler radar systems have been developed to measure ocean currents from shore-based stations (Paduan and Graber, 1997). Microwave Doppler radar systems have recently been developed and applied to measure the water surface velocities in rivers (Plant and Keller, 1990). These systems measure the Doppler shift of Bragg's scatter from random waves on the water surface. Yamaguchi (1996) has experimented with a few radar(s) to monitor water surface velocity across a river. Research is needed to determine the optimal radar frequencies, feasible incident angles, and the effects of electrical conductivity on signal dispersion.

PROOF-OF-CONCEPT EXPERIMENT

On April 21, 1999, the U.S. Geological Survey and the Applied Physics Laboratory of the University of Washington collaborated to carry out an experiment using radar technology that was designed to directly measure river discharge without any instrument having to touch the water (Costa et al, 2000). The non-contact discharge experiment took place at a USGS streamgaging site (12000500) on the Skagit River, Washington, about 100 km north of Seattle. The Skagit River is about 200 m wide, and averaged water depth is about 4.5 m, and the site has a cableway for suspending the GPR antenna to measure channel geometry. During the non-contact discharge measurement, concurrent independent measurements of river discharge were made by conventional current meter, by a moving boat method for river discharge using an ADCP, and by use of a long-term stage-discharge rating curve for the site (Fig. 2).

Fig. 2. Skagit River, WA with GPR antenna suspended from cableway, and ADCP boat measurement being conducted.

In the non-contact discharge experiment, a microwave Doppler radar operating at a frequency of 10 GHz was mounted on top of a van on the bank of the river (Fig. 3). The microwave radar measures remotely the Doppler shifts of the Bragg scattering from short waves produced by the turbulence associated with open-channel flow (Plant and Keller, 1990). The Doppler shift is used to estimate stream current along the radar beam direction. The radar measured velocity distribution is compared with velocities measured by a Price AA mechanical current meter. While it took about 10~15 minutes to make a velocity distribution measurement, it required about 2 hours for a conventional discharge measurement made by current meter and sounding weight.

Fig. 3. Microwave radar for scanning surface velocity.

By moving a GPR across the river, it produces a continuous high-resolution profile of the water surface and stream bottom by measuring the travel time of an electromagnetic pulse between a transmitter, a reflective boundary, and a receiver. It took about 8-10 minutes to complete one GPR measurement for water depth distribution. The GPR cross-section along with the two direct sounding weight measurements collected the same day. The GPR cross-sectional area at 1345 hours was computed to be 598 square meters (m^2) whereas the two sounding weight determined areas were 572 and 547m^2.

Two assumptions were made in computing the stream discharge in the Skagit River by non-contact radar measurements. The surface velocity was converted to mean velocity, and the velocity of radar waves in the river and air was estimated to convert GPR signal travel time to water depth. By assuming the velocity distribution is approximately logarithmic, the water column mean velocity is estimated to be 85% of surface velocity (Rantz, 1982). Three surface-velocity microwave radar readings were made (Figure 3).

Using the GPR-generated cross-section, and three radar-generated surface velocity data sets for estimates of mean velocity, three non-contact discharge values were calculated giving an averaged discharge of 518 m^3/s. At the same time, seven ADCP moving boat discharge measurements (passes) were made for comparison with discharge measurements. Average discharge for the seven ADCP measurements was 520 m^3/s, with the measured discharges ranging from 526 m^3/s to 511 m^3/s. A conventional current meter discharge measurement produced a discharge of 527 m^3/s. The computed non-contact discharge measurement is compared with ADCP and conventional discharge measurements along with the rating curve estimated discharges, (Table 1). The measured discharge using non-contact methods in the proof-of-concept experiment falls within the accuracy standards of conventional procedures. The next step in the proof-of-concept experiment was to consider making non-contact discharge measurements with radar from a single point on the river bank and from two points on the opposite sides of the river bank.

Table 2. Results of non-contact discharge computations.

Method	Time	Discharge (m^3/s)	Discharge from rating curve (m^3/s)
ADCP	1042	526	527
	1130	521	524
	1156	511	521
	1252	525	518
	1300	517	518
	1312	523	515
	1316	514	515
Mean		**520**	**520**
Current meter	1630	527	504
Non-contact radar	1253	518	518
	1305	517	518
	1339	520	515
Mean		**518**	**517**

PHASE II RADAR FIELD EXPERIMENTS

Upon the successful completion of the "proof-of-concept" experiment (Costa et al, 2000), the USGS has designed three additional experiments to remotely measure water surface velocity distributions from which river discharge is deduced. These experiments were designed to further test the various properties of radar technologies. The final results are still being evaluated, but these experiments are summarized and described.

Monostatic radar configuration

This experiment took place at the South Fork of Shenandoah River, VA, March 8-9, 2000, using a contractor with extensive experience in radar technology. A multi-frequency monostatic radar system was located on one bank of the river for measuring the water surface velocity and water depth distribution across the river. The objectives of this experiment were to measure surface velocity distribution across the river using the Doppler shift of Bragg's scatter and water depth distribution from the same radar mounted on one bank of the river. If successful, the combination of surface velocity and water depth will be used for computation of river discharge. In monostatic setting, the radar beam impinges the river at an oblique angle. The focus of this experiment is to determine whether the properties of backscattered radar signals can be correlated to river depth distribution across the river cross-section. The experiment was not successful, since it was not possible to identify the reflected radar signals returning from the bed of the river. During the experiment, the river discharge was assumed to be steady (from the rating curve) and the USGS collected extensive "truth" data for later comparison with radar measurements.

Bistatic radar configuration

The bistatic radar configuration was proposed and conducted by a second contractor. These experiments were carried out at two sites in California on June 5-7, 2000. The first study site is a trapezoid, concrete lined channel approximately 25 m wide, the Delta-Mendota Canal near Tracy, California. This site was selected because the channel cross-section has a simple geometry, which alleviates complications due to variable water depth. The second site is at the American River near Sacramento, California. A transmitter and a receiving antenna were set up on opposite banks. The equal travel time contours for radar signals are loci of ellipses with the transmitter and receiver as the focal points of these ellipses. The surface velocity is deduced based on the same principle of Doppler shift of Bragg's resonance. The proposed concept for monitoring the water depth is quite novel. The emitting radar waves arrive at the receiving antenna following two paths: a) direct transmission between the transmitter and the receiver and b) transmitted waves that refract at the water surface and then reflect off the bottom of the river (water-sediment interface) before returning to air and eventually to the receiving antenna. Since the radar wave travels at approximately nine times slower in water than in air, the time delay in arrival can be related to the water depth. At the American River, the cross-section of the experimental site is approximately 80 m wide. Again, this experiment was not successful. The identification of the river cross-section by radar from the bank of the river, without touching the water, is a very difficult physics problem, and has not yet been resolved.

Helicopter Radar Experiments

Because it was not possible to measure the channel cross-section of a river from the riverbank, a bridge or cableway would still be required in order to make non-contact discharge measurements. Another approach for getting the GPR antenna out over the water was needed. Following a similar approach to the "proof-of-concept" experiment in the Skagit River, we designed an air-borne radar experiment, again in collaboration with the Applied Physics Laboratory, University of Washington. Two sets of microwave radar transmitting and receiving antennas were mounted on the opposite sides of a helicopter looking sideways to monitor water surface velocity as the helicopter flys across a river. A GPR system was mounted on the bottom of the helicopter for monitoring river cross-section. On September 13, 2000, the radar equipped helicopter visited three rivers in southwest Washington State. Ground truth data were collected during the helicopter experiment. Good, usable data were collected on channel cross-section and the surface-velocity profile, but failure of the GPS system prevented us from establishing location throughout the flight that involved changing directions and velocities as wind conditions changed.

Figure 4. Helicopter-based streamflow measurements. HF and LF radar systems mounted on sides and bottom of helicopter.

A subsequent experiment was conducted using the same helicopter and radar equipment near the USGS streamflow-gaging station on the Cowlitz River at Castle Rock, Wash., on May 1, 2001. (DGPS) equipment was installed in the helicopter to ensure accurate positioning as the helicopter flew from one side of the river to the other. From 0840 PDT to 1025 PDT, river discharge was measured from a small boat attached to a tag line along the flight-path cross section by using standard USGS procedures. The measurement made by using a Price AA current meter and lead sounding weight yielded a discharge of 226 m^3s^{-1} (7,970 ft^3s^{-1}; median time of 0930 PDT). A second boat carried an acoustic Doppler current profiler (ADCP), which was used to measure velocity profiles at 31 positions across the river. Surface velocity values were then obtained by extrapolating the trend of the ADCP velocity profiles to the surface of the river. Results compared well with current-meter measurements obtained as close to the surface of the river as possible.

Results

These experiments provide insight into some of the operational conditions necessary to measure river discharge by using helicopter-mounted radar. The ideal helicopter speed for these measurements was about 3 knots, and the ideal elevation for data collection and safety was about 3–5 m above the water surface. The radar results were sensitive to the helicopter heading and flow direction. Discharge changed by about 0.5 percent for each degree of error in measured flow direction and by about 2 percent for each degree of error in heading. A good GPR signal was obtained using a 100 MHz unshielded antenna. By using the single best GPR profile combined with an average of eight pulsed-Doppler surface velocity data runs, these experiments produced mean velocity, mean depth, and resultant discharge values within 2.4 percent of values obtained by conventional methods. Safe collection of helicopter-derived discharge data is dependent on a careful reconnaissance and selection of river cross sections that have open banks for maneuvering on both sides of the river.

Table 3. Comparison of cross-sectional mean velocity and discharge from radar and conventional methods (current-meter measurement and stage-discharge rating curve)

Method	Mean Velocity	Mean Depth	Discharge
Sounding weight/ Current meter (0930 PDT)	1.67 m/s*	1.49 m*	226 m^3s^{-1}
Rating curve (stage-discharge relation)			
(0930 PDT)			222 m^3s^{-1}*
(1630 PDT)			222 m^3s^{-1}
Radar (1630 PDT)	1.63 m/s	1.52 m	223 m^3s^{-1}
Deviation from baseline data	-2.3 %	+2.0 %	+0.4 %

* Baseline data

Conclusions

The results of these proof of concept experiments indicate that it is possible to measure the actual discharge of the river within the accuracy standards of conventional procedures, using non-contact methods. To accomplish this, it is necessary to (a) convert surface-velocity to mean velocity for about 25 points across the surface of the river, by converting surface velocity to mean velocity in each subsection; and (b) convert radar-signal travel times to depth, by assuming the average speed of a radar pulse in impure fresh water to be 0.11 to 0.13 ft/ns.

These results demonstrate the feasibility of using non-contact methods for river discharge measurements; they also show that additional research on non-contact stream-discharge measurements is warranted. The increase in safety for field personnel and speed are advantages. The non-contact measurements each took about 15 minutes to complete, compared to 2 hours for a conventional current meter measurement. The ideal gaging station in the future would provide continuous discharge data by tracking stage, velocity, and cross-sectional geometry in real time by non-contact methods.

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